International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN (P): 2249-6890; ISSN (E): 2249-8001
Vol. 9, Issue 3, Jun 2019, 1085-1094

HOT DEFORMATION BEHAVIOUR STUDIES ON 58Ni-39Cr NICKEL SUPER ALLOY BY THERMO-MECHANICAL SIMULATION AND FINITE ELEMENT METHOD

B. S. R. VENU MADHAV & B. SURYANARAYANA

Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology

(Affiliated to Osmania University), Gandipet, Hyderabad, Telangana, India

ABSTRACT

As there is an increased requirement of materials with superior quality and excellent properties, there is a search for appropriate materials to satisfy the increasing demands of product requirement, which has led to the invention of numerous new materials such as Nickel Super alloys that have superior properties, like great toughness, high oxidation resistance. These materials are inducing extensive interest in distinct fields like Oil and Gas Industries, Marine Industries, Nuclear Reactors industries. The forging of the Material needs to be done at a temperature zone to avoid failure of the Material. The torrid plastic deformations of the Alloy have been explored using Gleeble 3500 simulator and the consequences of forging aspects have been studied. It is then compared with the simulation studies carried out, using a finite element-based simulation software tool, DEFORM™ 3D. The results from both studies indicate that there is an upsurge in the flow stress as the forging temperature is lowered and the strain rate is increased. Flow softening is observed at every deformation conditions, which can be reflected by a crest followed by a drop-in flow stress with further straining.

KEYWORDS: Deformation, Strain Rate, Temperature, Flow Stress, Microstructure, Thermo-Mechanical Processing & FEM Simulation

Received: Feb 08, 2019; **Accepted**: Feb 28, 2019; **Published**: Mar 23, 2019; **Paper Id.**: IJMPERDJUN2019116

Original Article

1. INTRODUCTION

Generally, the alloys are exposed to complicated time intervals, stress, strain rate and high temperatures in industrial forming operations. The consideration of the alloy behaviour under torrid deformation conditions has a huge impact for designing as metal-forming operations owe a huge influence over the metal flow sequence as well as the metallurgical transformation kinetics, in turn resultant mechanical properties including flow stress. Therefore, the investigation of stress-strain allocation is crucial for deformed materials for production process.

Ni-Cr-Mo Alloys have tremendous mechanical durability**,** suitable biocompatibility with atmosphere, steep modulus of elasticity, soaring melting point**,** ultra-low densities, immense hardness, resist to deflection, excellent adhesion properties with ceramics**,** accessible processing, high resistance to corrosion because of surface passivation, by creating chromium oxide film(Cr_2O_3) upon the alloy. Despite their attractive mechanical properties, susceptibility to corrosion of non-precious materials has limited their application because of corrosion products containing a variety of lethal metal ions. To embellish some unique characteristics, other materials are also combined with the alloy. When Molybdenum is added to the alloy, a solid solution is formed hardening the alloy

formation**.** Molybdenum forms intermetallic phases as well as forms precipitate which strengthens the alloy; Molybdenum is essential for reactions involving oxidation, as it surges the surface affinity for oxygen and develops resistance for pitting in electrolytes consisting chlorides.

The forecasting about stress-strain allocation and micro-structural expansion of torrid deformed Ni-Cr-Mo alloy is of high concern to the material designers. It consists of analysing the workability along with enhancing the sizzle forming characteristics. With the rising usage of FEM to outline the sample behaviour under the various phases of forging**,** awareness on constitutive relationships relating process parameters like temperature, strain rate and flow stress of the deforming material is a requisite**,** therefore it is imperative to access the flow stress [1]. Flow stress is defined as the transitory value of stress required to continue plastically deforming and flow stress is indicated as a function of temperature, stress and strain rate. Uni-axial compression test is frequently engaged method for producing data to analyse the flow stress behaviour and feasibility of the materials [2]. To access the flow behaviour of alloy and to determine the best operation parameters for thermo-mechanical processing, the data produced by compression testing of cylindrical test pieces are utilised [3]. In order to study the outcome of forging temperature, strain rate and flow stress hot compression analysis on Ni-Cr-Mo has been executed on Gleeble 3500 simulator. Investigation was done to determine the outcome of forging temperatures ranging from 1075°C to 1200°C, with a 25°C interval using the uni axial compression testing equipment. The strain rates were also varied from $1s^{-1}$ to $5s^{-1}$ covering the appropriate processing range. Additionally, the experimental procedure has been virtually replicated using a FEM simulation software namely DEFORM™ 3D.

2. EXPERIMENTAL PROCEDURE

Table 1: Chemical Composition of Experimental Specimen (%)

Element	Ni	Cr	Mo	C	Si	Mn	S
Percent	0.58	0.39	0.02	0.005	0.002	0.003	0.001

The Chemical configuration of the test piece is specified in Table 1. Gleeble 3500 (Dynamic Systems, Inc.), a thermo-mechanical simulator is used for uni-axial hot compression testing [4]. Cylindrical specimens with 10mm diameter, 13.9mm length are used for the compression tests. Both ends of the sample piece were parallel to ensure homogeneous deformation during testing. Graphite (up to 1000□C) is utilized as lubricant and between the anvil and sample piece tantalum foil (>1000□C) of width 0.1millimetre was utilized to refrain the contact of the sample surface and the anvil. FEM software was used to carry out the analysis virtually. The test piece was deformed till 66% along with that the flow Stress data was documented**.** The investigation of the specimens was carried out with isotherde environment. Gleeble systems are absolutely meant for keeping up homogenous temperature across various sections of isotherde planes at the halfway of the sample piece, indeed during cooling or heating spontaneously.

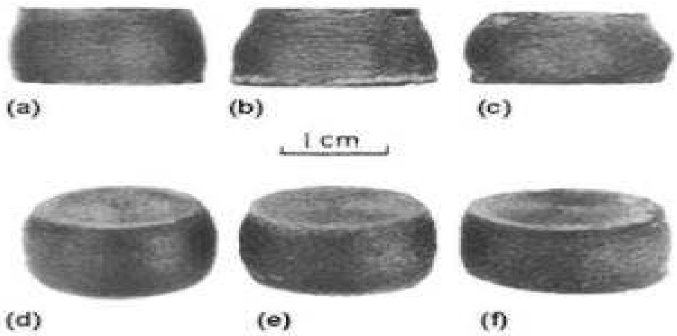


Figure 1: Hot-compression test specimens of Ni-Cr-Mo Alloy. Specimens (a), (b), (c) and (d) were tested at 1100°C, 1125°C, 1150°C, 1175°C at 1s^{-1} and (e), and (f) at 1125°C and 1175°C at 5s^{-1}. All specimens had an equiaxed microstructure before testing

3. RESULTS AND DISCUSSIONS

Microstructure of the Sample

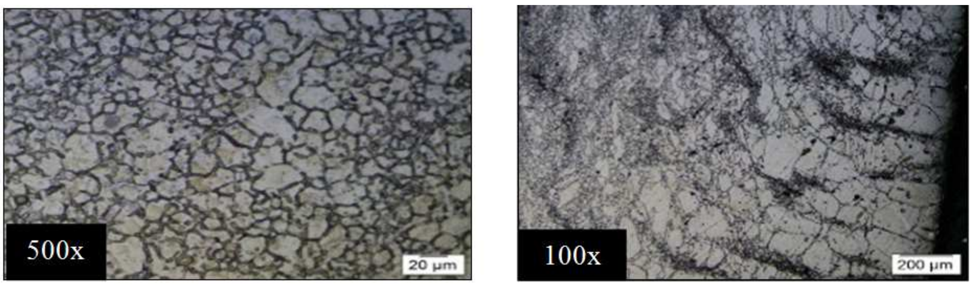


Figure 2: Strain Rate–1s^{-1} --Deformation Test Temp-1175°C for 60 sec

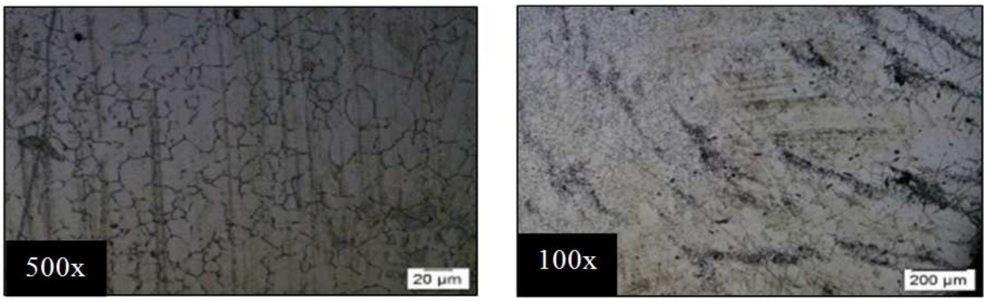


Figure 3: Strain Rate –5s^{-1} --Deformation Test Temp-1175°C for 60 sec

The microstructures of 1s^{-1} and 5s^{-1} strain rates at 1175°C are displayed in Figure 2 and 3, respectively. Initially the microstructure has stretched grain structure with tiny grains recrystallized near the boundaries at 1175°C. As the temperature is escalated, additional as well as bigger grains are created near the primary boundary; along with that necklace design was created. As the deformation temperature goes higher than 1100°C, there is a phase change of the Chromium alloy due to which the forging becomes easier. As the deformation is carried on, strain hardening is induced as the recrystallization grains are deformed; leading to the occurrence of secondary recrystallization, along with **a** combined form of pellucid microstructure is developed. The flow stress graphs exhibit fluctuations due to the maceration of secondary recrystallization. As the deformation temperature rises higher than 1100℃ at strain rate-1s^{-1}, the governing softening mechanism is by the cause of dynamic recrystallization furthermore the flow stress graph displays exemplary features as a result of dynamic recrystallization. Because of the extreme temperature, a little stress is enforced, and grain

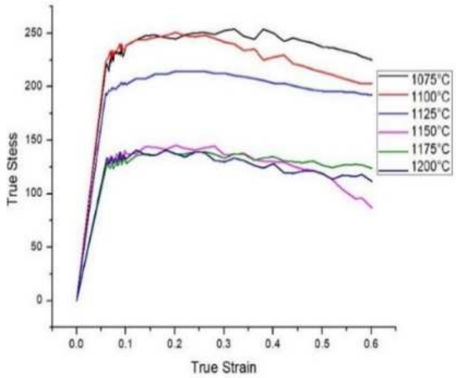
boundary slip i. e. movement of the gap atoms and vacancies take place at the grain boundaries leading to plastic deformation. As the temperature increases, the stress to be applied reduces.

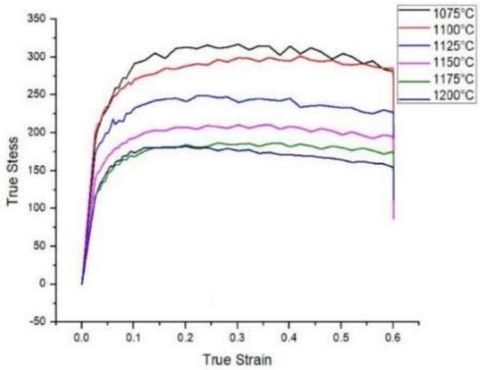
4. THERMO-MECHANICAL SIMULATION

An array of flow stress graphical representation was gathered all along the isothermal compression of Ni-Cr-Mo alloy with various deformation conditions and stain rates (Figure 4). It was observed that the flow stress properties of the Ni-Cr-Mo alloy are majorly determined by the strain rates & temperature as detailed below.

4.1 Effect on Flow Stress with Temperature

(Figure 4) shows the strain-stress graphs of the Ni super alloy deformed at various temperatures. It is noticed as the deformation temperatures rise; the flow stress lowers during the isothermal compression at each and every strain rates, indicating that the plastic deformation of the material is thermally activate. An increase in the temperature decreases the dislocation density resulting in lesser interaction between dislocations, and facilitating easier dislocation movement in deformation resistance of the material, as there is a rise in the temperature. In general, nature of the flow curves at all strain rates was similar. After peak stress, the curves generally revealed either a decreasing trend in flow stress or flattening owing to dynamic recovery.





(a) (b)

Figure 4: Flow Curves of Thermo-Mechanical Simulation Corresponding to various Temperatures at (a) 1 s^{-1} and (b) 5 s^{-1}

4.2 Effect on Flow Stress with Strain Rates

It is noticed that as the flow stress rises from 1s-1 to 5s-1 strain rate, because the dislocation-dislocation interaction rise in the alloy, and strain rate is crucial parameter for flow stress. From the observations, it is recorded that strain softening takes place at every strain rate and with an increase in strain rate; there is an increase in the peak strain for dynamic recrystallization.

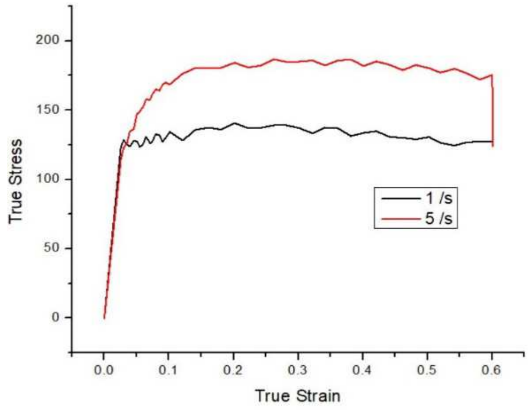


Figure 5: Flow Curves of thermo-Mechanical Simulation corresponding to various Strain Rates at 1175°C

4.3 Constitutive Flow Stress Equation

Deformation behaviors in Ni-Cr-Mo Alloy were further investigated through its constitutive characteristics. Presently, the investigation of torrid deformation behaviour was mostly done by the thermal compression or tensile tests to attain strain- stress graphs, and the Arrhenius equation with Zener-Holloman constant is brought in, that illustrates the constitutive equation at extreme temperatures as mentioned below [4, 5, and 6]:

$$Z = \acute{\varepsilon} \exp^{\left(\frac{Q}{RT}\right)} \tag{1}$$

$$\acute{\varepsilon} = A\, f(\sigma) \exp^{\left(\frac{-Q}{RT}\right)} \tag{2}$$

$$f(\sigma) = \begin{cases} \sigma^{n'} & for\ \alpha\sigma < 0.8 \\ exp(\beta\sigma) & for\ \alpha\sigma > 1.2 \\ [sinh(\alpha\sigma)]^{n} & for\ all\ \alpha\sigma \end{cases} \tag{3}$$

Constitutive modeling equation of flow stress consists of the following parameters: strain rate, stress, deformation temperature. The expression (4) represents Ni-Cr-Mo alloy at high temperature deformation conditions:

$$\sigma_p = \frac{1}{\alpha} sinh^{-1}\left(\frac{\acute{\varepsilon} exp\left(\frac{Q}{RT}\right)}{A}\right)^{1/n} \tag{4}$$

4.4 Constitutive Equation Verification

A contrast between the calculated and predicted peak stress by eq. (4) is executed to authenticate the constitutive equation of Ni-Cr-Mo Alloy at elevated temperatures, as demonstrated in below table. To access the precision of the constitutive equation the errors amidst the predicted peak stress (σp) and calculated stress (σm) were also estimated

$$Error\ (\%) = (\sigma p – \sigma m/\sigma m)\ x\ 100 \tag{5}$$

Considering the mean error in peak stress is predicted to be < 1% Thus, it can be observed that the estimated peak stresses agrees with the measured values.

Table 2: Values of Estimated Stress and Calculated Stress at various Temperatures and Strain Rates

Temp	Strain Rate	Predicted Stress(σp)	Measured Stress(σm)	Error (%)
1075	1	248.2357586	252.59571	-1.72605916
1100	1	218.8774899	241.83806	-9.49419214
1125	1	192.2513571	212.72822	-9.62583281
1150	1	168.3735275	177.94745	-5.38019654
1175	1	147.1866572	133.33352	10.38983838
1200	1	128.561695	129.74359	-0.91094675
1075	5	310.6580629	316.96657	-1.99027520
1100	5	278.6853349	299.12478	-6.83308320
1125	5	248.9555798	240.15547	3.664338701
1150	5	221.5521828	210.43939	5.280757
1175	5	196.530505	184.99846	6.233589744
1200	5	173.901667	176.27722	-1.34762336

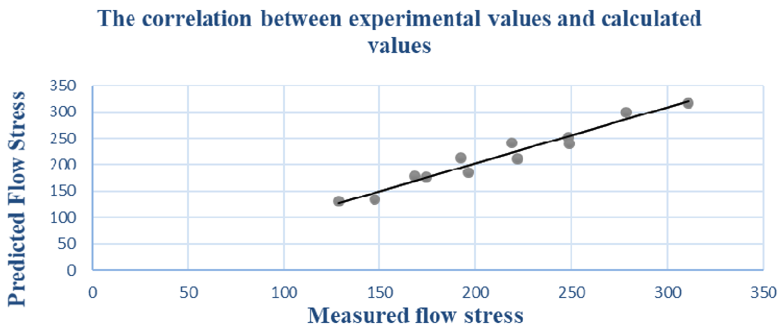


Figure 6: Correlation between Experimental Values and Calculated values

Therefore, the mean inaccuracy (%) is 0.93369.

Considering the measured information in the X-axis, along with estimated information calculated by the equation (2, 4) for the Y-axis, the connection amidst both is displayed in Figure 6. Given that data correlation judgment coefficient R is 0.97865, a decent data for the forging operation, design and simulation is provided by the developed constitutive equation.

5. FEM SIMULATION

The FEM simulation segment examines the stress-strain allocation curves due to impact of deformation temperature upon Ni-Cr-Mo alloy during torrid upsetting operations by inputting the thermo-mechanical parameters in finite element method, DEFORM-3D. The dimensions of initial billet are comparable to the test piece used in compression testing. The operation circumstances for the thermal physical characteristics and Simulation of the FEM software [7] of distorted sample block are:

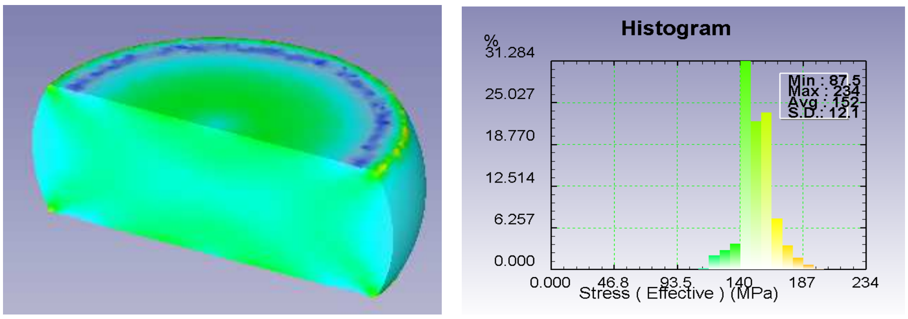
- The friction is considered to be shear type near the deformed tooling-block surface, and friction factor [8] was taken as 0.3 in the process of deformation;
- The material is considered to be deformed elastically and every die is considered as rigid body because of immense temperature & huge deformation in the process;
- The temperature of environment is taken as the room temperature i. e. 20°C;

- The convection coefficient is 0.02N/(s mm °C) to surroundings;
- The heat transfer coefficient is 5 N/ (s mm°C) amidst deformed block and die

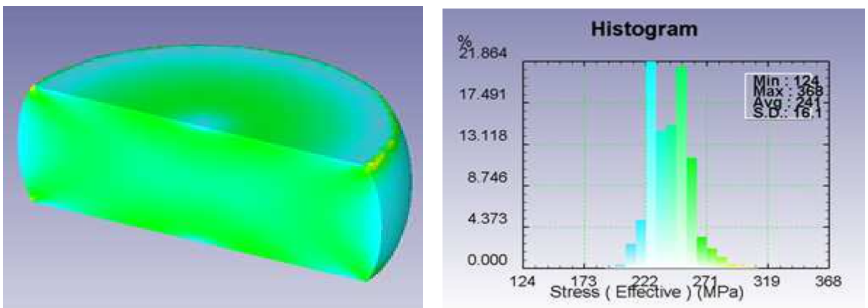
As the test piece is symmetrical, the results are only taken for half the sample block. The impact on the deformed piece is considered with the deformation temperature along with the stress-strain allocation with strain rate of 1s-1, 5s-1 and distortion extent of 66% are exhibited in Figure 7 (a) and Figure 7 (b) respectively. From the data generated, it can be noticed that the stress distribution in the sample due to deformation is inhomogeneous, and it can also be perceived that the utmost effective stress is found amidst of the sample piece. From the experimental results, it can be observed that with the alterations in deformation temperatures, the position of the maximum effective stress alters considering the deviations in deformation temperatures. It can also be assumed that the deformation areas with low strain as well as low deformation temperature values have the maximum effective stress. It is also found that the effective stress at the common boundaries for the large and small deformation range is almost large for the high deformation temperatures. From the experimental data, it can also be retrieved that with the rise in deformation temperature, there is a decrease in stress, as displayed below in Table 3.

Table 3: Load Measurement for Deformation

Ɛ	Temp	Stress Effective			Strain Effective			Load
		Max	Min	SD	Max	Min	SD	
1	1100	365	175	17.4	4.26	0.188	0.425	48100
	1125	292	176	13.1	6.17	0.162	0.408	40100
	1150	254	126	11.4	4.13	0.195	0.431	36000
	1175	234	87.5	12.1	5.22	0.195	0.346	29500
5	1125	384	200	15.6	6.7	0.178	0.369	49700
	1175	368	124	16.1	4.15	0.257	0.284	47400

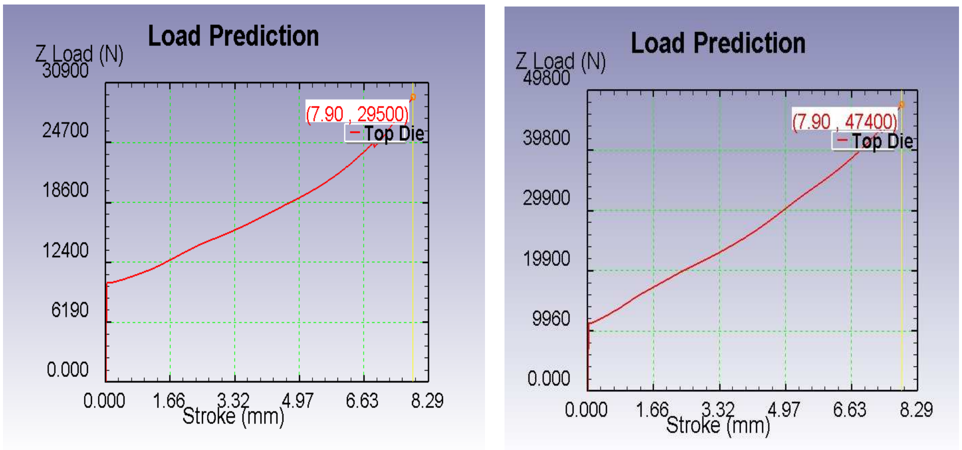


(a)



(b)

Figure 7: Effects of Deformation Temperatures on the Stress Distribution with the Deformation Strain Rate (a)1s^{-1} (b)5s^{-1} and Deformation Degree of 66% at 1175ºC



(a) (b)

Figure 8: Effects of Deformation Temperatures on the Load Stroke curve with the Deformation Strain Rate of (a)1s^{-1} (b)5s^{-1} and the Deformation of 66% at 1175°C

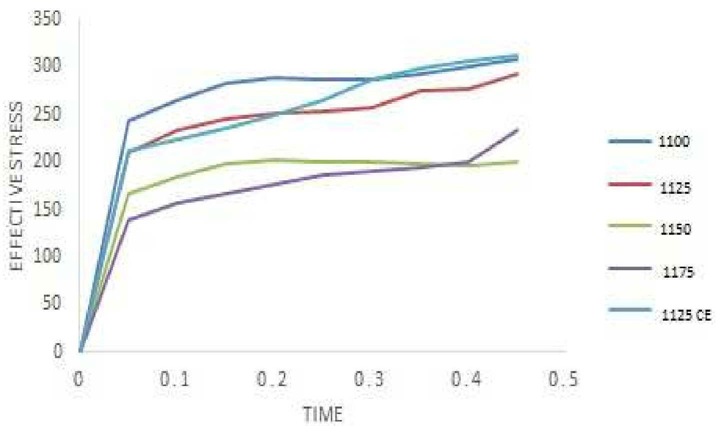


Figure 9: Graphs of Finite Element Simulation for the Strain Rate of 1s^{-1} at (a) 1100°C (b) 1125°C (c) 1150°C (d) 1175°C (e) 1125°C with Constitutive Equation

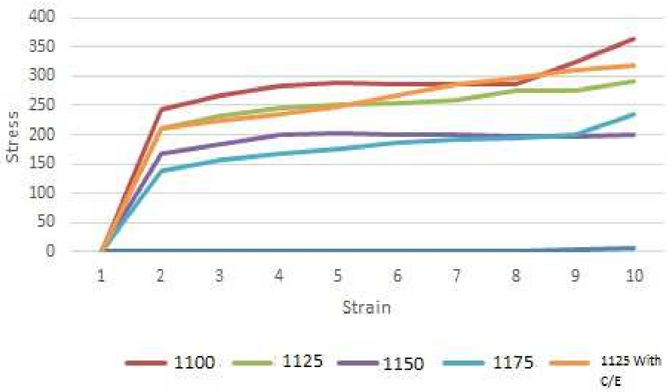


Figure 10: Graphs of Finite element simulation for Strain-Stress Analysis at: (a) 1100°C (b) 1125°C (c) 1150°C (d) 1175°C (e) 1125°C with Constitutive Equation

6. CONCLUSIONS

Considering the above experimental analysis, we have studied that Gleeble 3500 simulator has been used to investigate the impact of stress, strain rate and forging temperature of Ni-Cr-Mo alloy. Based on the testing situations, the Finite Element Modeling simulations were performed to contrast and certify the conclusions**.** The consecutive remarks are concluded:

- The results indicated that with the decrease of deformation temperature as well as increase in strain rate, the flow stresses of Ni-Cr-Mo Alloy increases. The following result has been established by a Zener-Hollomon parameter in the constitutive equation.
- When the material is subjected to lower strain rates & higher temperatures, the deformation mechanism of Ni-Cr-Mo Alloy is grain boundary slip and diffusion & on the other hand when the material is subjected to higher strain rate and higher temperature, the deformation procedure involves intracrystalline twin & slip.
- The flow strain-stress graph oscillates initially as the strain rate attains higher strain rate like $5s^{-1}$, and the vacillation vanishes eventually with the deformation enduring & the graph attains smoothness when the strain is > 0.3.
- Ni-Cr-Mo alloy is an example of strain rate sensitive material. With the surge in the strain rate, the flow stress rises considering that the deformation temperature is constant.
- Flow softening was observed at all deformation conditions, which were reflected by a peak followed by a drop in the flow stress with further straining. Flow softening was predominantly due to dynamic recrystallisation at lower strain rate of $1s^{-1}$.
- Using the linear regression analysis, the deformation activation energy 'Q' & strain hardening coefficient 'n' were calculated and then from the analysis, the constitutive equation of Ni-Cr-Mo at hot compression was developed. Predicted flow stress values at peak from constitutive equation developed matched very well with the experimental results with error being less than 1%.
- The Simulation results specify that the deformations of the sample piece are non-homogenous, and the maximum mean strain is located at amidst of the sample piece.
- Precision values are provided by the simulation results and the test results. Therefore, the hot compression experiments & Finite Element Modeling simulations provide a better productive means of deformation performance at the work piece.

REFERENCES

1. *N. K. Park, J. T. Yeom, Y. S. Na, Characterization of deformation stability in hot forging of conventional Ti-6Al-4V using processing maps, Journal of Materials Processing Technology, Vol. 130-131, 2002, p. 540-545.*
2. *RL Goetz, SL Semiatin, The adiabatic correction factor for deformation heating during the uniaxial compression test, J Mater Eng Perform, Vol. 10, 2001, 10, p.710*
3. *Y C Lin, GE Liu, A new mathematical model for predicting flow stress of typical high-strength alloy steel at elevated high temperature, Computational Material Science, Vol. 48, 2010, p. 54–8.*

4. *Y. C. Lin, Ming-Song Chen, Jue Zhong, Effect of temperature and strain rate on the compressive deformation behaviour of 42CrMo steel, journal of materials processing technology, Vol. 205, 2008, p. 308–315.*
5. *H. Shi, A. J. McLaren, C. M. Sellars, R. Shahani, R. Bolingbroke, 1997. Constitutive equations for high temperature flow stress of aluminium alloys, Mater. Sci. Technol., Vol. 13, p. 210–216.*
6. *H. Takuda, H. Fujimoto, N. Hatta, Modelling on flow stress of Mg–Al–Zn alloys at elevated temperatures, J. Mater. Process Technology. Vol. 80–81, 1998, p. 513–516.*
7. *Special Metals: Alloys Expert- Inconel alloy 690*
8. *George E. Dieter, Handbook of Workability and Process Design, Hot Compression Testing, Chapter 6, University of Maryland*